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The effect of angle of attack on flow-induced vibration of low-side-ratio rectangular cylinders

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ABSTRACT

This study investigates the effect of angle of attack on flow-induced vibrations (FIVs) of sharp-edged rectangular cylinders. In particular, the effect of the afterbody of a rectangular cross-section with low mass ratio and the side ratio ranging from 0.67 to 1.5 is analysed by changing the angle of attack with respect to the oncoming free-stream. As already shown for a different side ratio's rectangle, namely a square section (see Nemes et al., 2012), the angle of attack variation can make the flow-induced amplitude response switch between vortex-induced vibration (VIV) and galloping. Some considerations with respect to the interaction between the two phenomena typical of FIV, VIV and galloping, are also given for the side ratios of 1.5 and 0.67. The amplitude and frequency responses are carefully analysed, comparing the results with those of a square section of comparable mass ratio. The results showed a marked effect of the after-body, even for slight increments of the angle of attack. This can result in different amplitude response curves, as classified by the features of the response. In addition, the influence of interacting higher harmonics components on the amplitude response is also shown and discussed.

1. Introduction

This study examines the influence of the angle of attack variation on the flow-induced vibration (FIV) response of sharp-edged rectangular cylinders. The cross-section investigated has a side ratio ($SR = B/D$), defined as the ratio between the body width (B) and depth facing the fluid flow (D), of 1.5 in the zero angle of attack ($\alpha = 0^{\circ}$) configuration. The body is subjected to a free-stream water flow perpendicular to its long axis, and the cylinder is constrained to oscillate only transversely to the free stream. Generally, sharp-edged bluff bodies can be subjected to different forms of aeroelastic phenomena, such as flutter, galloping and vortex-induced vibration (VIV). For the SR range investigated here two phenomena have been found to occur, VIV and galloping. If galloping can be referred to as a divergent (not self-limited) aerodynamic instability, generally occurring in a higher range of reduced velocities, one can identify VIV as a self-limited phenomenon occurring in a bounded lower velocity range. It occurs when an elastic or elastically-mounted bluff body is immersed in a moving fluid and the occurrence of a fluctuating pressure distribution on the body may induce a vibrational response at certain velocities or

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natural frequencies. Given that galloping is caused by the aerodynamic forces induced by the transverse motion of the body, there can be no instability without an initial displacement condition.

Consequently, a body's motion implies a change of angle of attack, see for example Parkinson and Smith (1964) and as illustrated in Fig. 1. Thus, galloping is categorized as a type of movement-induced excitation (MIE), whereas VIV is categorized as a type of instability-induced excitation (IIE), given it is associated with the flow instability involving local flow oscillations (see Naudascher and Rockwell, 2005). These two phenomena will be discussed here and their mutual interference investigated. From here on they are referred as *interaction VIV–galloping* or simply *interaction*.

Vortex-induced vibration has been extensively investigated firstly on circular cylinders (e.g. Feng, 1968; Sarpkaya, 1979; Bearman, 1984; Sarpkaya, 2004), and then other body shapes (Bearman and Davies, 1977; Bearman and Currie, 1979; Bearman and Obasaju, 1982; Zhao et al., 2018a). In addition to the full understanding of the vortex shedding physics (Gerrard, 1966; Bearman, 1967; Perry et al., 1982) there has also been considerable interest in conceiving strategies for the suppression of transverse vibrations, caused by the non-linear resonance between the frequency of vortex shedding (f_{vs}), occurring for any body with an appreciable afterbody, and its natural (structural) frequency of oscillation (f_{n}). These studies were primarily conducted on circular section bodies because this means any consideration involving the orientation of the flow (or attack angle, α) can be neglected. As a result, researchers can focus mainly on the role played by the Reynolds number, (Re), in affecting other key features of the phenomenon, such as wake turbulence transitions, position of the separation points, lift and drag crisis, switching behaviour of the Strouhal number (St) in the super-critical range.

Apart from the practical engineering applications in civil and ocean engineering (light poles, power line cables, submerged structures *e.g.* offshore platform pillars, risers, wind turbine towers, mooring lines and spars), the circular section is taken as the canonical section for studying the singular effect of vortex shedding, as other forms of divergent instabilities (galloping or flutter) cannot occur, given the aerodynamic stability of the section. Conversely, for sharp-edged bluff bodies the separation points are fixed at the section's up-stream leading edge. In fact, the near-wake vortex structure presents a negligible Re-dependence, without changing flow regimes increasing its velocity. In contrast, it has been found that for the circular cylinder vortex shedding regimes depend on incoming flow velocity (Roshko, 1954; Bloor, 1964).

Galloping is an aerodynamic instability of slender non-axisymmetric structures caused by a self-excitation when the aerodynamic damping becomes negative. When a cross-section is aerodynamically unstable, as it is in this case, where there is a lack of axial symmetry, a characteristic of rectangular sections. According to the Glauert–Den Hartog incipient stability criterion (stating the instability of a system in case Eq. (1) is verified) (Glauert, 1919; Den Hartog, 1932), small-amplitude vibrations generate forces that increase in amplitude to large values as the flow velocity is increased.

$$\left.\frac{dC_{\mathrm{L}}}{d\alpha}\right|_{\alpha_0} + C_{\mathrm{D}}(\alpha_0) < 0, \tag{1}$$

where C_{L} and C_{D} are the lift and drag aerodynamic force coefficients defined in Fig. 1, while α_0 indicated the angle of attack at rest. To-date the only suitable theory to predict transverse 1-DoF galloping oscillations onset velocity and the post-critical regime is the quasi-steady theory (QS), which has been successfully applied by Parkinson and Smith (1964). Once the galloping onset velocity (Eq. (4)), which is proportional to the mass and damping ratio, is exceeded the system manifests itself as limit-cycle harmonic oscillations.

The dynamics of an elastically mounted body constrained to oscillate across the stream depends on the mass of the oscillating body, m, the mechanical damping c and the system elastic stiffness k (both assumed constant here), the fluid density ρ, the kinematic viscosity ν, and the free-stream velocity U. It is defined by the equation

$$m\ddot{y} + c\dot{y} + ky = F_y\left(t\right) \ , \tag{2}$$

where $F_y\left(t\right)$ represents the forcing imposed on the cylinder by the fluid. This leads to the key non-dimensional parameters of the system typically used for FIV: the mass ratio, $m^* = m/m_d = m/\rho V$, where m_d is the mass of the fluid displaced by the body, and $V = BDL$ the immersed body volume; and the damping ratio of the system in water,

$$\zeta_{\mathrm{w}} = c/\left(2\sqrt{k\left(m+m_A\right)}\right), \tag{3}$$

where m_A is the added mass. The added mass can be estimated from potential flow or measured directly through its influence on the natural frequency of the body in quiescent fluid. The reduced velocity is defined by $U^* = U/(f_{\mathrm{n}}D)$, where f_{n} is the natural frequency of the freely oscillating body in quiescent fluid and D is the cylinder's characteristic transversal dimension. In his pioneering paper on the VIV of a circular cylinder in air flow, Feng (1968) showed that a resonance condition can exist when the frequency of shedding, f_{vs}, and that of the body oscillation, f_{osc}, are synchronized when close to f_{n}. The maximum amplitude response, $A^*_{\max}$ =max(A/D), occurs in this lock-in region of $f_{\mathrm{vs}} \approx f \approx f_{\mathrm{n}}$, *i.e.* after the reduced velocity increases above, $U^*_r = 1/St$, where $St = f_{\mathrm{vs}}D/U$ is the dimensionless shedding frequency of a fixed cylinder.

According to QS-theory the galloping onset reduced velocity (U^*_g) is given, in a different non-dimensional form to that reported in Eq. 19 of Parkinson and Smith (1964), as a function of damping (ζ), geometry of the cross-section (B, D), fluid density (ρ), mass ratio (m^*) and slope of the lateral force coefficient around the zero angle of attack, that is $A_1 = \left(dC_{\mathrm{Fy}}/d\alpha\right)|_{0^\circ}$.

$$U^*_g = 2\pi\frac{2\zeta}{nA_1} = \frac{4m\zeta}{\rho D^2 L A_1} = \frac{Sc}{A_1\pi} = \frac{4\zeta m^*}{A_1}\frac{B}{D}\,, \tag{4}$$